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ETCHING METHOD OF HARDLY-ETCHED MATERIAL AND

SEMICONDUCTOR FABRICATING

METHOD AND APPARATUS USING THE METHOD

BACKGROUND OF THE INVENTION

The present invention relates to a method of
etching hardly-etched materials such as Pt, Ru, Ir,
PZT, HfO2 and the like, a semiconductor integrated
5 circuit device including hardly-etched materials, and a
method of manufacturing the same, and more
particularly, to technologies which are effective in
etching a side wall of a hardly-etched material
substantially to the perpendicular.

10   Conventionally, methods of etching
semiconductor devices using a tapered photoresist and a
rounded-head photoresist are known as means for
processing the surface of the semiconductor device.

A method of etching using a tapered mask is
15 disclosed in US Patent No. 5818107 (JP-A-10-214826) and
JP-A-10-223855. On the other hand, a method of etching
using a rounded photoresist is disclosed in US Patent
No. 6057081 (JP-A-10-98162).

However, a non-volatile material, which is
20 difficult to etch (hereinafter simply called a "hardly-
etched material), is etched at high temperatures higher
than 300°C, so that a photoresist may not be available.

SUMMARY OF THE INVENTION

With the miniaturization of semiconductor devices and faster operations, investigations are under progress about the use of such materials as alumina,
5   zirconium oxide, hafnium oxide, ruthenium, platinum, tantalum oxide, BST, SBT, PZT and the like for gate insulating films, gate electrodes of MOS (metal-oxide-semiconductor) transistors, and capacitors and capacitor electrodes of memories. In addition, nickel,
10   cobalt, and manganese, or their alloys are used for magnetic-based memories (MRAM: magnetic random access memory) and the like.

Hardly-etched materials may be exemplified by the following materials:

15   Magnetic Materials: (Applications: Magnetic Disk, MRAM, etc.) Fe, Co, Mn, Ni, etc.

Precious Metals, etc: (Applications: Various Electrodes, etc.)

Pt, Ru, RuO_2, Ta, Ir, IrO_2, Os, Pd, Au, Ti,
20   TiO_x, $SrRuO_3$, (La, Sr)CoO_3, Cu, etc.

High Dielectric Materials: (Applications: Capacitors of DRAM (for accumulating charge), etc)

BST: (Ba, Sr)TiO_3, SRO: $SrTiO_3$, BTO: $BaTiO_3$,
$SiTa_2O_6$, $Sr_2Ta_2O_7$, ZnO, Al_2O_3, ZrO_2, HfO_2, Ta_2O_5, etc.
25   Ferroelectric Materials: (Applications: Capacitors of FeRAM, etc.)

PZT: Pb(Zr, Ti)O_3, PZTN: Pb(Zr,Ti)Nb_2O_8,
PLZT: (Pb, La)(Zr, Ti)O_3,

PTN: PbTiNbOx, SBT: SrBi2Ta2O9, SBTN: SrBi2(Ta, Nb)2O9.

BTO: Bi4Ti3O12, BiSiO$_x$, BLOT: Bi$_{4-x}$La$_x$Ti3O12, etc.

5   Compound Semiconductors: GaAs, etc.

ITO, etc.: InTiO, etc.

These hardly-etched materials are hard to etch, as compared with such materials as aluminum, silicon, silicon oxide and the like, and therefore

10 present a problem in their difficulties in processing a side wall thereof perpendicularly to a substrate.

Any of the aforementioned known documents does not suggest processing a side wall of a hardly-etched material perpendicularly to a substrate.

15 Next, the following explanation will be given of reasons for difficulties in etching chemically stable materials to the perpendicular when using a plasma. The chemically stable materials include iron, cobalt, manganese, nickel, platinum, ruthenium,

20 tantalum, alumina, hafnium oxide, zirconium oxide, gallium arsenide and the like.

In the aforementioned hardly-etched materials listed above, which are difficult to etch, a reaction product is produced by etching. The reaction product

25 flies out of the surface of a sample into a vapor phase, and then reaches a wall of an etched material. The reaction product has the nature of readily attaching to the wall of the etched material as it

reaches there. If the reaction product attaches only
to a position at which the etched material is being
etched, this would substantially cause only a reduction
in the etching rate. Actually, however, the reaction
5   product attaches to any positions on the etched
material. Specifically, the reaction product also
attaches to a side wall of the etched material which is
not hardly being etched, so that, as a result, the
bottom of the etched material is being etched
10   simultaneously with the deposition of the reaction
product or a deposition material on the side wall.
Consequently, the etching fails to provide the side
wall of the etched material perpendicular to the
substrate. The foregoing is the cause of the failure
15   in providing a hardly-etched material with its side
wall perpendicular to the surface of the substrate in
etching the hardly-etched material.

          The foregoing reason for the failure in
providing an etched material with a side wall
20   perpendicular to a substrate will be explained in
greater details with reference to Figs. 1A through 2G.

          Figs. 1A, 2A illustrate an initial state of
etching, where arrows oriented to the right indicate a
direction in which a deposition material is deposited,
25   and arrows oriented downward indicate an etching
direction. Assume herein that the angle of a side wall
of a mask 10 to the top surface of a substrate (taper
angle) is at 90 degrees. As a short unit time Δt

elapses from the initial state, the bottom (the top
surface 21 of the etched material 20 exposed to a
plasma) is etched by Δe, and the deposition material 25
is deposited on the side walls of the mask 10 and the

5 etched material 20 by Δd (Figs. 1B, 2B). Actually, a
top surface 30 of the deposition material is also
etched, so that the angle ϕ of the top surface 30 to the
surface of the substrate (taper angle) is determined by
the amount Δd of the deposition material 25 deposited

10 per unit time (deposition rate), and the amount Δe of
etching per unit time (etching rate).

   In a portion 32 beneath the side wall of the
mask 10, at an instance the deposition of the
deposition material 25 begins on the side wall of the

15 mask 10, the etching is stopped for a bottom portion 33
of the deposition material on the side wall of the mask
10 (the top surface 21 of the etched material 20
exposed to the plasma). However, at an instance an
exposed portion of the etched material 20 is etched in

20 a lower portion of the side wall of the deposition
material 25 on the side wall of the mask 10, so that a
new side wall of the etched material 20 is exposed, the
deposition material is deposited on this exposed
surface. Consequently, the etched material 20 is

25 etched in a diagonally downward direction (Figs. 1C,
2C).

   Next, as another unit time Δt elapses from
the states illustrated in Figs. 1C, 2C, the deposition

material 25 is further deposited on the side wall of
the former deposition material 25, while an exposed
portion of the etched material 20 is etched in a lower
portion of the side wall of the deposition material 25

5 (Figs. 1D, 1E, 2D - 2F). In this manner, the etching
sequentially advances diagonally downward, resulting in
an etching shape as illustrated in Figs. 1F, 2G.
Eventually, the side wall of the etched material 20
forms a taper angle ϕ (ϕ < 90 degrees) to the surface of

10 the substrate.

It is therefore an object of the present
invention to provide a method of etching a hardly-
etched material, which is capable of solving the
problems inherent in the prior art, as well as a

15 semiconductor fabricating method and apparatus using
the etching method.

It is another object of the present invention
to provide a method and apparatus for processing the
surface of a sample, which is capable of consistently

20 processing a plurality of wafers, or forming a taper
angle of an etched material close to the perpendicular,
for responding to the requirement for miniaturization
of semiconductor devices and the like.

The present invention is characterized by a

25 plasma-based surface processing method which uses a
tapered mask to etch a sample or a film formed on a
substrate.

Specifically, according to one aspect of the

present invention, a plasma-based etching method is
provided for etching a film of hardly-etched material
formed on a substrate using the film and a mask formed
on the hardly-etched film. The method includes the
5 step of etching the film of hardly-etched material
using the mask having a side wall angled at less than
90 degrees with respect to the surface of the
substrate.

Thus, according to the present invention, for
10 etching a material which is hard to form with a
perpendicular side wall, the etched material can be
formed with a side wall close to the perpendicular by
the use of a tapered mask, thereby fabricating high
performance semiconductor devices or highly integrated
15 semiconductor devices.

Other objects, features and advantages of the
invention will become apparent from the following
description of the embodiments of the invention taken
in conjunction with the accompanying drawings.

20 BRIEF DESCRIPTION OF THE DRAWINGS

Figs. 1A - 1F are cross-sectional views for
explaining an etching process using a mask having a
perpendicular side wall;

Figs. 2A - 2G are cross-sectional views for
25 explaining an etching process using a mask having a
perpendicular side wall;

Fig. 3 is a diagram generally illustrating an

exemplary configuration of a plasma etching apparatus to which the present invention is applied;

Figs. 4A – 4D are cross-sectional views for explaining an etching process when a taper angle θ of a

5   mask is chosen to be less than 90 degrees;

Figs. 5A – 5D are cross-sectional views for explaining the relationship between the deposition of a deposition material on a side wall of a mask and a taper angle ϕ of an etched material when the taper angle

10 θ of the mask is gradually reduced from 90 degrees;

Fig. 6 is a graph showing the relationship between the taper angle of the mask and the taper angle of the etched material;

Figs. 7A, 7B are diagrams showing the

15 relationship between the taper angle of the mask and the taper angle of the etched material when the taper angle of the mask is in a region smaller than a limit value, and when in a region equal to or larger than the limit value;

20 Figs. 8A – 8E are diagrams for explaining a method of controlling the taper angle of the mask by manipulating components of an etching gas and an etching pressure;

Figs. 9A – 9E are diagrams for explaining a

25 method of controlling the taper angle of the mask by wet etching;

Figs. 10A – 10I are diagrams for explaining a method of controlling the taper angle of the mask by

wet etching;

Figs. 11A - 11I are diagrams for explaining another method of controlling the taper angle of the mask by wet etching;

Figs. 12A - 12D are diagrams for explaining a method of controlling the taper angle of the mask by dry etching and wet etching;

Figs. 13A - 13D are diagrams for explaining another method of controlling the taper angle of the mask by dry etching and wet etching;

Figs. 14A - 14F are diagrams for explaining a method of substantially providing the effect of a tapered mask by using a mask, the taper angle of which is substantially 90 degrees;

Fig. 15A is a block diagram illustrating an exemplary configuration of a semiconductor device fabricating apparatus to which the present invention is applied;

Fig. 15B is a block diagram illustrating another exemplary configuration of the semiconductor device fabricating apparatus to which the present invention is applied;

Figs. 16A - 16D are diagrams for explaining a method of substantially providing the effect of a tapered mask in a ferroelectric memory by using a mask, the taper angle of which is substantially 90 degrees;

Figs. 17A - 17D are diagrams for explaining a method of substantially providing the effect of a

tapered mask in an MRAM by using a mask, the taper angle of which is substantially 90 degrees; and

Fig. 18 is a cross-sectional view for explaining an etching process using a mask having a

5 perpendicular side wall.

DETAILED DESCRIPTION OF THE EMBODIMENTS

In the following, one embodiment of the present invention will be described in detail with reference to the accompanying drawings.

10 Fig. 3 is a diagram generally illustrating an exemplary configuration of a plasma etching apparatus to which the present invention is applied. A coil 103 is supplied with a high frequency current from a high frequency power supply 101 through an automatic

15 matching unit 102 to generate a plasma 105 in a vacuum chamber 104. The vacuum chamber 104 is comprised of a discharge section 104a made of an insulating material, and a processing section 104b connected to a ground. An etching gas such as a chlorine is introduced into

20 the vacuum chamber 104 through a gas introducing port 106, and exhausted from an exhauster 107.

A sample 108 is carried on a sample base 109. For increasing the energy of ions incident on the sample 108, a bias power supply 110, which is a second

25 high frequency power supply, is connected to the sample base 109 through a high pass filter 111. An insulating film 112 made of ceramic or the like is coated on the

surface of the sample base 109. A direct current power
supply 113 is also connected to the sample base 109
through a low pass filter 114 for electrostatically
holding the sample 108 on the sample base 109.

5   The sample base 109 is further provided with
a heater 115 and a coolant flow passage 116 for
adjusting the temperature of the sample 108 to control
the processing.

          Typical conditions for etching a chemically
10   stable material using the plasma etching apparatus are
detailed below. Chemically stable materials include
iron, cobalt, manganese, nickel, platinum, ruthenium,
tantalum, alumina, hafnium oxide, zirconium oxide,
gallium arsenide and the like. The apparatus is
15   maintained at a pressure of 0.5 Pa, and chlorine is
mainly introduced into the apparatus. Though depending
on an etched material under processing, the temperature
of the sample 108 is in a range of 200°C to 500°C.
Though the temperature is determined by a required
20   etching rate, or a particular semiconductor device to
be fabricated, the sample 108 is maintained at high
temperatures as compared with typical temperatures in a
range of 0°C to 100° C when a silicon film, an aluminum
film or a silicon oxide film is etched. Due to the
25   high temperature, it is often the case that a
photoresist cannot be effectively used for a material
of a mask for use in etching, and instead, a hard mask
made of silicon oxide, metal or the like is used in

many cases.

It is contemplated to solve the aforementioned problem in etching a hardly-etched material, i.e., for etching an etched material to form a taper angle ϕ of the etched

5 material close to the perpendicular to the surface of a substrate, it is critical to suppress the amount of deposition material attaching to the side wall of the mask.

It is contemplated to reduce the pressure

10 within a reaction chamber, and increase the flow rate of a gas introduced into the reaction chamber as a method of suppressing the deposition of the deposition material. However, the pressure in the reaction chamber and the flow rate of the gas are often limited

15 within proper ranges for achieving desired etching characteristics, and moreover, the limits of the pressure and flow rate are determined by an exhaust capability. It is therefore difficult to suppress the deposition of the deposition material by manipulating

20 the pressure, flow rate and the like.

Next, referring to Figs. 4A - 5D, the following explanation will be focused on the reason for the ability to process an etched material with a taper angle (the angle of the side wall of the etched

25 material to the top surface of the substrate) ϕ close to the perpendicular by using a mask, the taper angle (the angle of the side wall of the mask 10 to the surface of the substrate) θ of which is less than 90 degrees. Fig.

5A shows the etching process when the taper angle θ of
the mask is chosen to be 90 degrees, in which case a
deposition material 25 is deposited in parallel with
the side wall of the mask 10, as previously explained
5 in connection with Figs. 1A - 2G. Fig. 4A in turn
shows a state before etching when the taper angle θ of
the mask is chosen to be 90 degrees.

First, as the process conditions are
determined, an etching rate is determined for the
10 bottom of the sample (a surface 21 of the etched
material exposed to a plasma). As the sample is etched
using chlorine as a main etching gas, chlorides
(reaction product) of the etched material of the sample
fly out the substrate (sample)into the etching
15 apparatus (reaction chamber). The reaction product
flying out into the etching apparatus again impinges on
the substrate, and some of the reaction product
impinging on the substrate is deposited on the surface
of the substrate (the side wall of the mask, and the
20 side wall of the etched material) as a deposition
material (Fig. 4B). In many cases, the deposition
material can be approximated to be isotropic. The
deposition rate of the deposition material (hereinafter
simply called the "deposition rate") is represented by
25 rd. On the other hand, the etching mainly relies on
the action of ions, so that the etching rate is largely
affected by a direction in which the ions impinge at a
position of the etched material at which it is to be

etched. Assuming that the etching rate is simply determined by the flux of ions, the etching rate is represented by resin α, where re is the etching rate for the bottom of the sample when the ions impinge

5 substantially perpendicular thereto, and α is the incident angle of the ions. It should be noted that re is the true etching rate when no deposition material is deposited.

In other words, when the side wall of the

10 mask is perpendicular to the surface of the substrate, the deposition rate of the deposition material to the side wall of the mask is represented by rd, and an apparent etching rate on the bottom 21 of the sample is represented by re-rd (see Fig. 4D). In this event, the

15 taper angle ϕ of the etched material is given by:

$$\tan \phi = (re-rd)/rd$$

On the other hand, as illustrated in Figs. 4B, 5B, when the side wall of the mask is inclined slightly from the perpendicular to the surface of the

20 substrate (the taper angle θ of the mask is less than 90 degrees), the deposition rate to the side wall of the mask is represented by rd since it is isotropic, while the etching rate on the side wall of the mask is represented by re $\times$ cos θ. Thus, rd-re $\times$ cos θ

25 represents the deposition rate to the side wall when the taper angle of the mask is θ. Consequently, as

illustrated in Fig. 4D, the taper angle ϕ of the etched material is given by:

$$\tan \phi = (re-rd)/((rd-re \times \cos \theta) \times \sin \theta)$$

5   In this manner, under a condition in which the deposition material is being deposited on the side wall of the mask, as the taper angle θ of the mask is smaller, the taper angle ϕ of the etched material is larger after etching. Fig. 4C illustrates the mask 10 and etched material 20 from which the deposition
10   material has been removed after the etching process as illustrated in Fig. 4B.

As the taper angle θ of the mask is gradually reduced from 90 degrees further from that shown in Fig. 5B, the taper angle θ matches the taper angle ϕ of the
15   etched material ($\theta = \phi$), as illustrated in Fig. 5C. This state represents a condition that no more deposition material is deposited on the mask. Specifically, even if the deposition material is deposited on the mask, the deposition material is
20   instantaneously etched away, so that no deposition material attaches to the mask, as a result. Assuming that the taper angle of the mask is $\theta 0$, and the taper angle of the etched material is ϕm in this condition, the taper angle of the etched material will not exceed
25   ϕm even if the taper angle θ of the mask is further reduced (i.e., $\theta < \theta 0$), as illustrated in Fig. 5D.

Specifically, as illustrated in Fig. 5D, when $\theta < \theta 0$, θ < ϕm stands, causing the taper angle $\theta 0$ of the mask to reach a limit value at which the taper angle ϕ of the etched material is at maximum (ϕm). In the state

5 illustrated in Fig. 5D, the mask or underlying material (etched material) is exposed.

The relationship between the taper angle θ of the mask and the taper angle ϕ of the etched material is as shown in Fig. 6. Here, rd/re is uniquely determined

10 by the mask, the nature of the etched material and etching conditions (the pressure in the reaction chamber, the flow rate of a gas introduced into the reaction chamber, and the like). Generally, rd/re is smaller as the pressure in the reaction chamber is

15 higher, and rd/re is smaller as a larger flow rate of a gas is introduced into the reaction chamber.

As shown in Fig. 6, for example, when rd/re = 0.5, as the taper angle θ of the mask is reduced from 90 degrees, the taper angle ϕ of the etched material is

20 increased substantially in proportion to the taper angle θ of the mask. As the taper angle θ of the mask is reduced to 72 degrees, the taper angle ϕ of the etched material is correspondingly increased to 72 degrees ($\theta = \phi$), reaching the state illustrated in Fig.

25 5C. In other words, $\theta = \theta 0 = \phi = \phi$m stands. Therefore, even if the angle θ of the mask is further reduced ($\theta <$ $\theta 0$), the taper angle of the etched material remains at ϕm.

Thus, in Fig. 6, a line L indicates the limit value $\theta 0$ of the taper angle of the mask. It can be seen from the foregoing that the deposition material attaches to the mask in a region A where $\theta > \theta 0$, and the

5 taper angle ϕ of the etched material is determined by the taper angle θ of the mask. On the hand, in a region B where $\theta \cdot \theta 0$, the deposition material does not attach to the mask, and the taper angle ϕ of the etched material remains at the constant value ϕm irrespective

10 of the taper angle θ of the mask. Therefore, for example, when rd/re = 0.4, if the taper angle ϕ of the etched material is to be set at 70 degrees, the taper angle θ of the mask may be set at approximately 82 degrees.

15   Next, explanation will be given of a method of forming a mask with a side wall having a taper angle less than 90 degrees. In the following explanation, a Pt film is etched using a hard mask made of silicon oxide, as an example.

20   (a) Referring to Figs. 8A - 8E, explained first is a method of controlling the taper angle of the side wall of the silicon oxide which serves as a mask by manipulating components of an etching gas and an etching pressure. A hard mask material 51 made of a

25 silicon oxide film or a metal film is formed on a Pt film 50, and an overlying photoresist 52 is patterned into a predetermined pattern (Fig. 8A). Next, using an additive gas mainly consisting of a fluorocarbon based

gas, oxygen and the like, the silicon oxide film is
etched in a tapered shape (Fig. 8B). In this event,
the silicon oxide film can be etched into a tapered
shape by switching the composition of the gas

5 introduced into the etching chamber, and changing the
etching pressure.

Such etching into a tapered shape is
described, for example, in J. Vac. Sci. Technol. A14,
1832 (1996). This document describes a method of

10 controlling a taper angle of a silicon oxide film by
manipulating components of an etching gas, and an
etching pressure. Specifically, under etching
conditions including the use of a photoresist having a
taper angle of 86°, a flow rate of CF4 at 20 sccm, and

15 bias power at 100 W, the formed taper angle of the
silicon oxide film changes from 80° to 51° by changing
the pressure from 40 mTorr to 300 mTorr. Also, under
etching conditions including the pressure at 40 mTorr
and a total flow rate of CHF3 and CHF4 at 20 sccm, the

20 taper angle of the silicon oxide film changes from 66°
to 84° by changing the component ratio of the etching
gas (CHF3 in CF4 (%)) from 0% to 50%.

In this manner, it is understood that the
taper angle of the oxide film can be controlled by

25 making use of the fact that the etching rate for the
silicon oxide film in the horizontal direction is
substantially independent of the pressure, whereas the
etching rate in the vertical direction is reduced as

the pressure is increased.

When the taper angle of the silicon oxide film can be formed less than 90 degrees (Fig. 8B), the photoresist 52 is removed (Fig. 8C). Next, the

5   substrate is carried to a predetermined position in the etching apparatus for etching (Fig. 8D), and then, the mask 51 is removed (Fig. 8E).

Another etching method for forming the taper angle of the mask less than 90 degree is described in

10   U.S. Patent No. 5,856,239.

(b)   Next explained will be a method of forming a silicon oxide film, serving as a mask, with a taper angle of less than 90 degrees by wet etching. Such a method is disclosed, for example, in Jpn. J.

15   Appl. Phys., Vol. 34 (1995), pp. 2132-2136. Specifically, as illustrated in Fig. 9A, a polysilicon film 52 in a predetermined pattern is formed on a silicon oxide film 51 which serves as a mask for etching a Pt film 50, and immersed in an HF solution

20   under a constant condition. While the polysilicon film 52 is not etched by the HF solution, the silicon oxide film 51 is isotropically etched by the HF solution, and accordingly formed into a tapered shape as illustrated in Fig. 9B. Subsequently, the polysilicon film 52 is

25   etched using chlorine Cl2, fluorine F2, hydrogen hexafluoride SF6 or the like, to eventually form a silicon oxide mask 51 having the shape as illustrated in Fig. 9C. Thus, the Pt 50 film is etched using the

tapered mask as illustrated (Fig. 9D), and then, the mask 51 is removed (Fig. 9E).

Figs. 10A – 13D show several methods of forming masks made of silicon oxide film having

5   different taper angles with the same width (size).

First, a method shown in Figs. 10A – 10I forms masks having the same width (size) and different taper angles by manipulating the film thickness of a silicon oxide film 51 serving as a mask, and a wet

10   etching time chosen for a particular film thickness. For example, silicon oxide films 51 having different thicknesses T1, T2, T3 have been formed as illustrated in Figs. 10A, 10D, 10G, respectively, and then HF-based wet etching is conducted for a time in accordance with

15   each thickness of the silicon oxide film, resulting in the formation of masks having different taper angles, as illustrated in Figs. 10B, 10E, 10H, respectively. Therefore, as the polysilicon film 52 is removed afterwards, the resulting masks are formed with the

20   same width (size) and different taper angles θ1, θ2, θ3, respectively, as illustrated in Figs. 10C, 10F, 10I (where θ1 > θ2 > θ3). As can be seen, a smaller taper angle can be set for the mask as the silicon oxide film 51, as the mask, has a larger film thickness.

25   A method shown in Figs. 11A – 11I forms masks having the same width (size) and different taper angles by manipulating the width (size) of a polysilicon film, which serves as a mask, and a wet etching time chosen

for a particular width. For example, the polysilicon films 52, which serve as a form and a resist, are formed with different widths (sizes) W1, W2, W3, as illustrated in Figs. 11A, 11D, 11G, respectively, and

5 then, HF-based wet etching is conducted for a time in accordance with a particular width (size) of the polysilicon film 52, resulting in the formation of masks having different taper angles, respectively, as illustrated in Figs. 11B, 11E, 11H. Therefore, as the

10 polysilicon film 52 is removed afterwards, the resulting masks are formed with the same width (size) and different taper angles $\theta 4$, $\theta 5$, $\theta 6$, respectively, as illustrated in Figs. 11C, 11F, 11I (where $\theta 4 > \theta 5 > \theta 6$). As can be seen, a smaller taper angle can be set for

15 the mask as the polysilicon film 52 has a smaller width (size).

Figs. 12A – 13D show methods of controlling the taper angle by dry etching and wet etching.

In a method shown in Figs. 12A – 12C, a

20 polysilicon film 52 is first patterned into a predetermined width (size) W4 (Fig. 12A), followed by dry etching which substantially perpendicularly removes a portion of a silicon oxide film 51 by a thickness Th1 (Fig. 12B), followed by wet etching which forms the

25 silicon oxide film 51 into a tapered shape (Fig. 12C).

In a method shown in Figs. 13A – 13D, a polysilicon film 52 is first patterned into a predetermined width (size) W5 different from the

aforementioned width (size) W4 (Fig. 13A), followed by
dry etching which substantially perpendicularly removes
a portion of a silicon oxide film 51 by a thickness Th2
different from the foregoing thickness Th1 (Fig. 13B),
5 followed by wet etching which forms the silicon oxide
film 51 into a tapered shape (Fig. 13C).

In this manner, when the polysilicon films 52
used in Figs. 12A, 13A have the same thickness Th, the
taper angle of the mask can be set smaller as the
10 polysilicon film 52 has a smaller width (size), and the
taper angle of the mask can be set smaller as the
silicon oxide film 51 is etched by a smaller thickness.

In addition, the taper angle of the mask can
be controlled by combining the foregoing tapered mask
15 forming methods.

Now, the explanation will be made with
reference to Fig. 3 as to the case for etching a Pt
film having a thickness of 0.5 μm using an SiO_2 mask
and the etching apparatus of Fig. 3.

20 As described above, a gas for use in the
etching mainly consists of chlorine, and the Pt film is
etched with a bias voltage applied to a wafer. In this
event, since the SiO_2 mask is etched substantially at
the same rate as the Pt film, the SiO_2 mask must have a
25 thickness similar to that of the Pt film or more.
Assume here that the SiO_2 mask has a thickness of 0.5
μm.

In the apparatus of Fig. 1, the ratio rd/re

is equal to or higher than a constant value under a
condition in which a plasma can be stably maintained.
Assume here that a minimum value of rd/re is 0.4. In
this event, it can be seen from Fig. 6 that when the
5 SiO2 mask has a taper angle of 90°, the Pt film has a
taper angle of 57° after the Pt film is etched. That
is, the width y of the bottom surface of the resulting
Pt film is larger than the SiO2 mask by about 0.3 μm at
each of the side portions of the film (that is, x1 = x2
10 = 0.3 μm). This is derived from the expression of x1 =
x2 = 0.5 μm + tan ϕ = 0.5 μm + tan 57°. Thus, assuming
that the total width of the mask is 0.5 μm, the total
width y of the bottom surface of the Pt film is about
1.1 μm (that is, y = 0.5 μm + x1 + x2 = 1.1 μm) when the
15 Pt film is etched by 0.5 μm.

However, if the SiO2 mask has been previously
formed with a taper angle of 80° and is used for etching
the Pt film under the same condition, the Pt film has a
taper angle of 70° after being etched, and the width y
20 of the bottom surface of the resulting Pt film is
larger than the SiO2 mask by about 0.2 μm at each of
the side portions of the Pt film and has the total
width y of about 0.9 μm (that is, y = 0.5 μm + x1 + x2
= 0.9 μm).

25   In this manner, by reducing the taper angle
of the mask, the taper angle at which the Pt film is
etched is increased. In other words, the shape
resulting from the etching can be controlled by

manipulating the taper angle of the mask.

When the taper angle of the mask is further reduced (for example, to 60°), the taper angle at which the Pt film is etched is further increased, however,

5 giving rise to a problem that the mask is etched because no deposition material is deposited on the mask in this condition.

It is appreciated from the foregoing that a condition under which the taper angle is larger and the

10 bottom surface of the mask maintains the size before etching is that the taper angle of the mask is chosen to be $\theta 0$. This taper angle $\theta 0$ of the mask can be predicted from the result of etching using a vertical mask. Specifically, assume that an angle ϕ (for

15 example, 60°) is measured as a result of etching using a vertical mask. In this event, it is estimated from Fig. 6 that the value of rd/re is 0.37 under that condition. In an equation:

$$\tan \phi = (re-rd)/((rd-re \times \cos \theta) \times \sin \theta)$$

20 a value estimated for rd/re (0.37 in this case) may be substituted to find θ which satisfies $\phi = \theta$ (77°).

(c) Next, referring to Figs. 14A - 14F, explanation will be given of a method of substantially providing the effect of a tapered mask even using a

25 mask made of silicon oxide having a substantially perpendicular side wall (i.e., the taper angle of which

is substantially 90 degrees). First, using a mask made
of silicon oxide 51 having a substantially
perpendicular side wall, a Pt film 50, i.e., an etched
material, is etched by a predetermined amount, for

5   example, one-half of a desired etching amount (Fig.
14B). As described above, in this state, a deposition
material 55 attaches to the side wall of the mask of
silicon oxide 51 (Fig. 14B). Next, the deposition
material 55 is removed (Fig. 14C). The deposition

10 material 55 is typically removed by a wet process which
uses pure water, ammonia water, sulfuric acid,
hydrochloric acid, alcohol, or a mixture of some of
them. After removing the deposition material 55, the
Pt film 50, which is the etched material, has a

15 protrusion 50a, the taper angle of which is $\phi 1$. After
removing the deposition material 55, the Pt film 50 is
again etched by the remaining amount to complete the
etching of the desired amount (Fig. 14D). In this
event, a deposition material 56 is deposited on side

20 walls of the mask of silicon oxide 51 and the
protrusion 50a of the Pt film 50. The deposition
material 56 is deposited in a similar manner to the
first deposition material 55. The Pt film 50 is
exposed on the side wall of a protrusion 50b of the Pt

25 50 film resulting from the second etching. The
protrusion 50b of the Pt film 50 thus formed has a
taper angle $\phi 2$ (where $\phi 1 < \phi 2$). In this manner, the
first etching and the immediately following removal of

the deposition material result in the substantial
tapered mask having the taper angle φ1, comprised of the
silicon oxide 51 and the protrusion 50a of the Pt film
50, as illustrated in Fig. 14C. The taper angle of the
5   etched material can be made close to the perpendicular
by using such a substantial tapered mask.

In addition, by repeating the etching and the
removal of the deposition material a plurality of
times, the taper angle of the etched material can be
10 brought closer to the perpendicular. When the Pt film,
which is the etched material, is exposed instead of the
deposition material on the side wall in the shape
provided immediately after the etching, the Pt film is
advantageously etched immediately during overetching.
15 If the deposition material is exposed, the deposition
material should be first etched, followed by etching
the Pt film, the etched material, during overetching.
Thus, also advantageously, a time required for the
overetching can be reduced.

20   Next, a method of removing a deposition
material will be explained.

A deposition material may be removed by a
process using super critical water or CO2, or by a dry
process using a proper gas, in addition to the wet
25 process. The dry process may be conducted using the
same processing apparatus (the same reaction chamber)
as the etching process for a Pt film. Further, etching
at a certain instance and etching at another instance

may be performed using the same etching apparatus (the same reaction chamber) or different etching apparatuses (different reaction chambers).

5   The dry process may be a plasma process which involves introducing, for example, oxygen, hydrogen, ammonia, chlorine, hydrogen chloride, or alcohol to generate a plasma, and removing the deposition material with the plasma.

10   Another wet-based method may involve exposing the deposition material to a mixture of super critical carbon dioxide with ammonia, alcohol, hydrochloric acid, or hydrogen peroxide to remove chlorides attached on a side wall.

15   In addition, a rinse step and a dry step may be interposed before or after the deposition material removing step as required. For example, when a deposition material is removed by a wet process using a chemical, the deposition material removing step may be followed by a washing step using pure water, and a
20   subsequent dry step. The etching performed in the foregoing manner provides a point in the middle of a side wall of a mask or an etched material at which a taper angle (suddenly) changes. In other words, it is possible to provide a portion in the middle of the side
25   wall of the mask or etched material at which the taper angle apparently changes. It should be noted that most of metal chlorides are water soluble.

Next, the present invention will be explained

when it is applied to a semiconductor device
fabricating apparatus with reference to Figs. 15A, 15B.

A semiconductor device fabricating apparatus
illustrated in Fig. 15A is a multi-chamber type
5   semiconductor device fabricating apparatus which
comprises an etching processing chamber 901; a wafer
carrying robot 903; a load lock chamber 904; an unload
lock chamber 905; a loader 906; and a stocker 907. A
cassette 908 is placed in the stocker 907. For
10 processing a wafer in the processing chamber 901, a
wafer 105 accommodated in the cassette 908
substantially in an atmospheric condition is carried
into the load lock chamber 904 substantially in an
atmospheric condition by the loader 906, and the load
15 lock chamber 904 is closed. After reducing the
pressure in the load lock chamber 904 to a proper
level, the wafer 105 is carried into the processing
chamber 901 by the wafer carrying robot 903, and is
etched to the middle. Subsequently, the wafer 105 is
20 carried into a deposition material removal processing
chamber 902 by the wafer carrying robot 903 to remove a
deposition material attached on side wall. Next, the
wafer 105 is again carried into an etching processing
chamber 901' by the wafer carrying robot 903 and etched
25 by a desired amount. Then, the wafer 105 is carried
into a deposition material removing processing chamber
902' by the wafer carrying robot 903 to remove a
deposition material attached on the side wall. Next,

the wafer 105 is carried into the unload lock chamber
905 by the wafer carrying robot 903. After increasing
the pressure in the unload lock chamber 905
substantially to the atmospheric pressure, the
5 processed wafer is inserted into the cassette 908 by
the loader 906.

    In this manner, Fig. 15A illustrates a
semiconductor device fabricating apparatus which
comprises a wafer carrier (903); a plurality of
10 processing chambers (901, 901') and a plurality of
post-processing chambers (902, 902') connected to the
wafer carrier; a plurality of lock chambers (904, 905),
and an atmosphere carrier (906) located adjacent to the
lock chambers, where the atmosphere carrier can be
15 connected to the plurality of lock chambers and a wafer
cassette (908) adjacent to the atmosphere carrier.
After a material under processing is etched in any of
the plurality of processing chambers, the material
under processing is post-processed in any of the
20 plurality of post-processing chambers. Subsequently,
the material under processing is again etched in any of
the plurality of processing chambers, and further post-
processed in any of the plurality of post-processing
chambers.

25   While the exemplary apparatus of Fig. 15A
employs the atmosphere cassette, a vacuum cassette may
be used instead as shown in Fig. 15B. Specifically,
Fig. 15B illustrates a semiconductor device fabricating

apparatus which comprises a wafer carrier (903); a
plurality of processing chambers (901, 901') connected
to the wafer carrier; a plurality of lock chambers
(904, 905); and an atmosphere carrier (906) located
5 adjacent to the lock chambers, wherein the atmosphere
carrier can be connected to the plurality of lock
chambers, a post-processing chamber (902) adjacent to
the atmosphere carrier, and a wafer cassette (908). A
material under processing is etched in any of the
10 plurality of processing chamber, and then post-
processed in the post-processing chamber.
Subsequently, the material under processing is again
etched in any of the plurality of processing chambers,
and post-processed in the post-processing chamber.

15   Further, while the deposition removing
process is performed in a vacuum condition for
convenience of explanation, this process may be
performed in an atmospheric condition.

        In the foregoing exemplary apparatuses, the
20 two etching processes are performed in the different
etching processing chambers 901, 901'. Alternatively,
the same process chamber 901 may be used a plurality of
times. An advantage provided by using another
processing chamber as an etching process chamber lies
25 in the ability to stably etch stacked films in
different conditions for the respective types of films.
The etching as well as the removal of deposition
material may be performed in the same chamber.

Next, referring to Figs. 16A - 16D,
explanation will be given of a method of etching
stacked films such as Pt/PZT/Pt, which constitutes a
memory area of a ferroelectric memory, using the method
5   (c) illustrated in the aforementioned Figs. 14A - 14F,
using a substantially tapered mask. In this method, if
the Pt/PZT/Pt films 61 - 63 are processed by a single
etching process as illustrated in Fig. 16A, a
deposition material will be inevitably deposited on
10 side walls of these films 61 - 63, resulting in the
shape illustrated in Fig. 16D. Specifically, the
dimensions of a mask 64 largely differ from the
dimensions of a resulting etched material. This
difference in dimensions will hinder the
15 miniaturization.

To avoid this inconvenience, immediately
before etching the conductive (for example, Pt) film 61
underlying the insulating film (PZT) 62, the etching is
interrupted to remove a deposition material (Fig. 16B).
20 This results in the PZT/Pt films 62 - 63 having a taper
angle $\phi3$. Subsequently, as the etching is resumed, the
shape as illustrated in Fig. 16C is provided. In the
illustrated shape, the Pt film 61 has a taper angle $\phi4$
(where $\phi3 < \phi4$). Characteristically, the films of the
25 same conductor (for example, the Pt films 61, 63),
formed on and below the insulating film (PZT) 62, have
different taper angles $\phi3$, $\phi4$. Of course, the taper
angle $\phi4$ can be set larger than a taper angle $\phi5$ shown

in Fig. 16D.

In this manner, the first etching and the immediately following removal of the deposition material result in a substantial tapered mask having

5   the taper angle $\phi 3$, comprised of the insulating film (PZT) 62 and conductive (for example, Pt) film 63, as illustrated in Fig. 16C. By using such a substantial tapered mask, an etched material included in stacked films can be formed with a taper angle close to the

10 perpendicular.

Next, referring to Figs. 17A – 17D, explanation will be given of a method of etching stacked films in MPAM (magnetic random access memory), which is expected as a memory device of the next

15 generation, using the method (c) illustrated in the aforementioned Figs. 14A – 14F, or the method illustrated in the aforementioned Figs. 16A – 16C, using a substantial tapered mask.

An MRAM has stacked films as illustrated in

20 Fig. 17A, which comprise, from above, a ferromagnetic material (for example, Co) 76; an insulating film (for example, Al2O3) 75; a ferromagnetic material (for example, Co) 74; an antiferromagnetic material (for example FeMn) 73; and underlying materials (for

25 example, Co and Si) 72, 71. The MRAM also includes a film 70, for example, a silicon oxide film 70. In the MRAM, it is required to etch these films 71 – 76 using a single mask.

In this event, if a larger amount of reaction product attaches on the FeMn film 73, for example, than on the other films, the etching is interrupted immediately before the etching of the FeMn film 73 is

5   started to remove the deposition material (Fig. 17B). This results in the films 74 - 76 having a taper angle $\phi6$. Subsequently, as the etching is resumed, the FeMn film 73 can also be etched into a shape close to the perpendicular (Fig. 17C). At this time, the FeMn film

10 73 has a taper angle $\phi7$ ($\phi6 < \phi7$). In this manner, the first etching and the immediately following removal of the deposition material, as well as the second etching and the immediately following removal of the deposition material result in a substantial tapered mask comprised

15 of the films 73 - 76, the taper angle of which changes halfway, as illustrated in Fig. 17C. By using such a substantial tapered mask comprised of the films 73 - 77, the etched materials 71, 72 can be formed with a taper angle $\phi8$ close to the perpendicular in the stacked

20 films of the MRAM and the like (here, $\phi6 < \phi7 < \phi8$).

The ferromagnetic material may be prevalently Fe, Co, Ni, Nn or a compound thereof, which are all known as hardly-etched materials. In Figs. 17B - 17D, a mask 77 is also shown.

25   The foregoing example has been taken for explaining a method of creating a mask shape or a substantial tapered mask shape for forming an etched material with a substantially perpendicular side wall.

A method according to the present invention explained below relies on a change in etching conditions to provide an etched material with a substantially perpendicular side wall.

5   As described above, the taper angle of an etched material is determined by the ratio rd/re of a deposition rate rd to a side wall of the etched material to an etching rate re to the bottom of the etched material. As the ratio rd/re is smaller, the

10   taper angle of the side wall of the etched material can be brought closer to the perpendicular.

          In the foregoing embodiments, the etching is conducted in conditions which make the deposition material difficult to attach to the wall of the vacuum

15   chamber (104 in Fig. 3), but a reduction in the concentration of a reaction product in the vacuum chamber is effective for reducing the attachment of the deposition material. Under conditions in which no deposition material attaches to the wall of the vacuum

20   chamber, a reduction in the concentration of a reaction product in a vapor phase can relay only on exhaustion of the reaction product in the vapor phase out of the vacuum chamber, or on forced attachment of the reaction product onto side walls of a mask and an etched

25   material. Therefore, actually, the concentration of the reaction product in the vapor phase is maintained high under the conditions in which no deposition material attaches to the wall of the vacuum chamber.

However, it is possible to make the reaction
product readily attach to the wall of the vacuum
chamber 104 in Fig. 3 by reducing the impedance of the
load (heater) 115 to reduce a current flowing an
5   electrostatically coupled antenna 118. In this event,
since the reaction product in the vapor phase attaches
to the wall of the vacuum chamber, and its
concentration is reduced accordingly, a reduction is
achieved in the amount of the reaction product
10 attaching to a wafer from the vapor phase. As a
result, a less amount of deposition material is
deposited on the side walls of the mask and etched
material, so that the etched material can be formed
with the side wall close to the perpendicular, even
15 using a mask having a side wall angled substantially at
90 degrees.

However, if the deposition material attaches
to the wall of the vacuum chamber, this will cause a
change in the state of a plasma, and the generation of
20 particles, so that the deposition material must be
periodically removed from the wall. Specifically, a
deposition material removal process (i.e., increasing
the current flowing the electrostatically coupled
antenna 118) is performed each time one or a plurality
25 of wafers have been processed.

In this event, the deposition material may be
rapidly exhausted out of the vacuum chamber 104 by
increasing the temperature of the wafer base (sample

base) 109 from that during etching to prevent the
deposition material from attaching to the wafer base
109. On the contrary, the temperature of the wafer
base 109 may be reduced to allow the deposition

5 material to actively attach to the wafer base 109 or a
wafer carried on the wafer base 109, to prevent the
deposition material from reflecting from the wafer base
109 or the wafer carried on the wafer base 109, such
that the deposition material is prevented from again

10 attaching to the wall of the vacuum chamber to promote
the exhaustion of the deposition material.

According to the present invention, for
etching a material which is hard to form with a
perpendicular side wall, the etched material can be

15 formed with a side wall close to the perpendicular by
the use of a tapered mask, thereby fabricating high
performance semiconductor devices or highly integrated
semiconductor devices.

It should be further understood by those

20 skilled in the art that the foregoing description has
been made on embodiments of the invention and that
various changes and modifications may be made in the
invention without departing from the spirit of the
invention and the scope of the appended claims.